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CORRELATION ANALYSIS AND POWER-LAW PROFILES OF LDV, PIBAL, AND ANEMOMETER (TOWER) WIND DATA IN THE REDSTONE ARSENAL BOUNDARY-LAYER

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Correlation analysis of windspeed in the Redstone Arsenal, Alabama boundary-layer along with the variation of the exponent in the power-law wind profile for concurrent tower, LDV, and pibal data are presented for 36 cases between 13 January and 1 April 1986. Wind profiles were available up to 90 m, 450 m, and 915 m for the tower, LDV, and pibal data, respectively. The correlation between the scalar wind at 4 m with the scalar wind at 90 m is .84 for the tower data improving to .92 when the scalar wind at 19 m is correlated with the scalar wind at 90 m. The correlations derived from the LDV data set also showed the correlations improving as the reference point is raised, but the correlations were lower and dispersed over a wider range.

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The mean and standard deviation of the exponent (P) in the power-law wind profile equation was calculated for each observation height. The overall mean P-value for the pibal data was .16, in close agreement with a value of 1/7 often quoted in the literature. There were more interlevel differences in the P-value for both the tower and LDV data sets. The overall mean P-value for the tower and LDV data were .11 and .07, respectively.

CONTENTS

I. INTRODUCTION

The relationship between wind conditions in the lower boundary layer and winds above has always been of interest to meteorologists. In general, in the lower friction layer it is assumed that the wind veers according to a theory developed by Ekman.[1] Numerous articles have appeared since that time, and Lettau[2,3] has devoted two texts to dealing with various problems of this friction layer. It may be superfluous to add merely another report.

The Ekman spiral, although well suited for many applications, has one drawback which may be a handicap in various cases. The theory requires the knowledge of the frictional conditions of the terrain and the top of the friction layer which can vary between 500 to 1500 meters depending on geographic latitude and friction parameters.

We have taken a different approach utilizing a special set of data observed at Redstone Arsenal, Alabama between 13 January and 1 April 1986. The relationship of low-level winds with winds above up to nearly 1 kilometer have been explored by analyzing concurrent pibal, anemometer (instrumented tower), and Laser Doppler Velocimeter (LDV) wind measurements. The analysis is divided into two parts. The correlation analysis consists of linear correlation coefficients of scalar windspeed at selected heights near the surface with scalar windspeed at altitudes above for the three different measurement systems. Correlations of the wind components (zonal and meridional) near the surface with wind components at altitudes above are included in most cases.

The second part of the analysis concerns the "power-law" equation for windspeed variation in the boundary-layer, in which the windspeed at a desired height is a function of the ratio of the reference height to the desired height raised to an exponent ("P"). A comparison of the exponent in the power-law equation for the three measuring techniques is made.

II. THE DATA

From 64 available days for measurement between 13 January and 1 April 1986, the concurrent LDV and tower data consisted of two measurement sets per day on 12 days and one measurement set per day for 12 days, for a total of 36. All of these measurements were taken during the late morning or early afternoon. Pibal measurements were available to compare the concurrent LDV and tower data except for the first observation point (19m). There were 35 coinciding pibal and tower measurements as the first pibal ascent was missing. The heights at which windspeed and direction were observed with the pibal single-theodolite system were the surface (approximately 4m) to 3000 feet in 100 foot increments. For the instrumented tower these heights were 4, 10, 19, 34, 61, and 90m. The LDV data set revealed that there was some variation of the observation heights; however, the wind data were primarily recorded for 19, 34, 61, 90, 153, 240, 336, 450, and 480m.

The tower wind and pibal wind are fundamentally different measurements; therefore, some differences between the two measurements are to be expected. The tower wind represents a measurement at a fixed point (a Eulerian system). The pibal winds are mean winds centered at 100-foot increments. The pibal winds are an approximate Lagrangian system because space and time variability are inherent in these measurements.

The analysis of the tower data was confined to the first two minutes of available data, a series of 120 one-second values. The LDV takes 3 to 5 seconds between measurements at different levels, and 30 to 35 seconds to return to the same level to take a new measurement. Therefore, 4 LDV observations in succession correspond to an approximate time period of 2 minutes. The pibal data were recorded less precisely than the tower or LDV data, in which windspeeds were reported in 0.001 m/sec units, although these data are generally regarded as accurate to the 0.1 m/sec. The pibal data were rounded to the nearest integer in the data provided to us. One should take into account that both the tower and pibal observations include smoothing while the LDV data may be considered as instantaneous measurements.

The pibal and anemometer data were furnished to us by the Redstone Meteorological Team who are supported by the Atmospheric Sciences Laboratory, U.S. Army Electronics Command, White Sands, New Mexico. The source of the LDV data was a private contractor.

Additional analyses have been made with this data set that appear in other reports, e.g., frequency distributions of windspeed and wind direction for each of the measurement techniques at overlapping heights, a comparison of the dispersion of the LDV and tower-measured winds, frequency distributions of windspeed and wind direction differences between surface and specified altitudes, and point-by-point correlations of two measurement techniques at the same height (i.e., pibal with tower and LDV with tower). (See References 4, 5, and 6.)

III. CORRELATION ANALYSIS

Table 1 lists the linear correlation coefficients of the scalar wind at a height of 4m with the scalar wind at indicated altitudes (r_s), the zonal wind component at 4m with the zonal wind component at indicated altitudes (r_z), and meridional wind component at 4m with the meridional wind component at indicated altitudes (r_m) for both pibal and tower data. The correlation of the scalar wind measured at 4m with the scalar wind measured at 34m is .95 for the pibal and .88 for the tower. As expected, these correlations decrease with height. For example, the correlation of the pibal scalar wind at 4m with the pibal scalar wind at 480m is reduced to .57.

Table 2(a) lists the correlations of the scalar winds at 19m altitude with scalar winds above for LDV and tower data. The correlations for the tower data were nearly identical for three conditions in Table 2A.

(1) Using all available observations

(2) Only the first observation from each data set for one time period

(3) Two-minute average.

For example, the correlation of the scalar wind at 19m tower height with the scalar wind at 34m tower height was found to be .95 for conditions (1) and (2) above. The correlations calculated for the LDV data are similar to those computed from the tower data for cases (1) and (3) (smoothed data), but are much

lower when using only the first observation (case 2). Since the LDV measurements are sensitive to the short-term wind fluctuations, it may be desirable to include an averaging process by representing more stabilized wind field conditions.

A variable number of wind profiles comprise one LDV data set (36 sets total). Table 2(b) lists the correlations of windspeed at 19m with windspeeds at altitudes above using the first, second, third, and fourth wind profiles available from each LDV data set. A similar analysis of windspeed correlations is provided in Table 2(c). The correlations obtained from the LDV data were dispersed over a wide range, in contrast to the correlations derived from the tower data which were very stable. This result indicates a need to use an averaging process for the LDV observations (Reference 6).

Table 3 provides a comparison of the correlations obtained from the tower data for three different reference points, 4m, 10m, and 19m. The correlation of the scalar wind at 4m with the scalar wind at 19m is .91, improving to .98 when the scalar wind at 10m is substituted as the reference point (Case 1). The correlation of the scalar wind at 4m with the scalar wind at 34m is .88, but raising the reference point to 10m improves the correlation to .94 (Case 1). A similar pattern was found for other heights. Furthermore, the correlations are only slightly lower when considering the first observation only (Case 2).

Table 4 lists the correlations of surface (approximately 4m) pibal winds with tower winds at the indicated heights. By substituting the surface pibal wind for the lowest tower wind, the correlations drop slightly. The correlation of the surface pibal scalar wind with the scalar wind at the 61m tower observation is .81, compared to .85 when using the lowest tower reference.

Table 5 lists the linear correlation coefficients of the scalar wind at altitudes of 34m, 61m, and 90m with the scalar wind at indicated altitudes (r_z), and the meridional wind component at 34m, 61m, and 90m with the meridional wind component at indicated altitude (r_m) for the pibal. The correlation of the scalar wind measured at 34m with the scalar wind measured at 153m is .95. However, the correlation of the scalar wind measured at 34m with the scalar wind measured at 240m decreases to .79. The correlation of the scalar wind at 61m with the scalar wind at 153m is .97, decreasing to .75 when the scalar wind at 61m is correlated with the scalar wind at 336m. Raising the reference point from 61m to 90m did not change these correlations significantly.

Table 6 lists the correlations of the winds measured at 34m and 61m with the winds measured at 61m and 90m for the tower data. It should be noted that these are correlations of one-minute average windspeeds. Considering the scalar windspeed only, the correlation of the wind measured at 34m with the wind measured at 90m is .96. Similarly, the correlation of the wind measured at 61m with the wind measured at 90m is .98.

In Table 7, the tower winds measured at 34m, 61m, and 90m were correlated with the pibal winds above. The correlation of the scalar wind measured at 34m with the scalar wind measured at 153m is .82. The correlations of the scalar wind measured at 34m with the scalar winds measured at 240m and 335m are .80 and .73, respectively. Nearly identical results were obtained when the winds at 61m and 90m were substituted as reference points.

Table 8 lists the correlations of the two-minute average windspeed measured at 34m, 61m, and 90m with the two-minute average windspeed measured at the indicated altitudes above for the LDV data. The correlation of the scalar wind measured at 34m with the scalar wind measured at 153m is .86, improving to .96 when the scalar wind at 61m is substituted as the reference point.

The correlation of the scalar wind observed at the tower with the scalar wind from the pibal at the same altitude was .81 at 34m and .82 at 61m (Reference 6). The correlation between the tower and pibal scalar winds at 150m reported by Rider and Armandariz (References 7, 8, and 9) for a site in Utah was .86, which agrees well with these results.

IV. POWER-LAW PROFILES

One purpose of this study was to evaluate a simple scheme for predicting the windspeed profile up to about 400m given the windspeed close to the ground. Various forms of the logarithmic windspeed profile have been utilized successfully. After evaluating the errors in computed winds using the power law and logarithmic law, Demarrais (Reference 10) concluded that the logarithmic wind profile will yield overall results comparable to the power law only if a stability parameter is added. He did point out that the logarithmic law performed better than the power law under superadiabatic conditions. However, his wind data did not go above 125m. Frost, et.al. (Reference 11) also concuded that the logarithmic law with stability parameter wind profile would no longer be applicable. Windspeed profiles will deviate from logarithmic above 100 to 150m (References 12, 13 and 14). This profile also requires estimating the surface local friction velocity for each type of terrain. Therefore, the power-law windspeed profile was selected for our purpose.

The power-law wind profile is a well-known formulation due to Frost (Reference 15) for determining the windspeed U_h at a desired height Z_h:

$$U_h = U_o(Z_h \mid Z_o)^P \tag{1}$$

where U_o is the windspeed at the reference height Z_o. This model is primarily intended for representing mean wind profiles as opposed to instantaneous wind conditions. The accuracy of the model is dictated by the proper choice of the exponent P:

$$P = \frac{\ln U_h - \ln U_o}{\ln Z_h - \ln Z_o} \tag{2}$$

The exponent P was calculated for each simultaneous pibal (single measurement) and tower observation (one-minute average windspeed). These are the same observational data as reported in Reference 6, noting that there were 35 coinciding pibal and tower observations. (The first pibal ascent was missing.) Each of these points are plotted in Figures 1(a), 1(b), 2(a), 2(b), 3(a), and 3(b) for the coinciding observation heights of 34m, 61m, and 90m, respectively. The reference height (Z_o) for both the pibal and tower data is 4m. These scatter diagrams indicate considerable fluctuation of the "P-values", which is not unexpected. These fluctuations are related to changes in atmospheric stability. The range of the P-values for the tower data is -0.37 to +0.38 at 34m and is -0.10 to +0.34 at 90m. The range of the P-values for the pibal data were found to be 0.0 to +0.32 at 100 feet (34m) and -0.22 to +0.35 at 300 feet (90m).

The mean and standard deviation of P for the tower and pibal data are listed in Tables 9(a) and 9(b), respectiely. The mean P-values are displayed in Figure 4. The mean P-values for the two measurement techniques are very similar at 34m, but the difference widens at 61m and 90m. This may be partially attributed to the different precision of the wind measurements in which the pibal and tower winds are reported with 1 and 4 significant figures, respectively. Beginning with 300 feet, the P-value for the pibal data is nearly constant at approximately .17. The dispersion of the P-values as indicated by the standard deviation will generally decrease with height as the measurements become less influenced by the retarding effects of the surface, but increase at higher altitudes (e.g., 2500 feet) as the power law becomes less appropriate.

The mean and standard deviation of the P-values derived from the LDV data are listed in Table 10. Note that the reference point is 19m, the lowest available measurement from the LDV data set. Therefore, these values cannot be directly compared to the P-values derived from the tower and pibal. The individual P-values (using 2-minute average LDV windspeeds) are plotted in Figures 5(a), 5(b), 6(a), 6(b), 7(a), and 7(b) for 153m, 240m, and 336m. The mean P-values for all available heights are plotted in Figure 8. A P-value of approximately .08 was derived for the 153m, 240m, and 336m heights. The dispersion of the P-values at these heights was less than at heights both above and below.

During the day when superadiabatic and neutral lapse rates are dominant, DeMarrais (10) found average P-values to vary between 0.1 and 0.3. DeMarrais further demonstrated that the P-values were considerably larger during neutral conditions than for superadiabatic conditions. This accounts for the scatter of P-values in the data obtained in this study. Brook and Spillane (16) surveyed the power-law profiles obtained by several other researchers and concluded that a mean P-value close to 1/7 is applicable in open terrain, particularly with near neutral lapse rates and strong mean winds.

At night when the atmospheric stability is varying between stable and inversion conditions, DeMarrais found that the values of P varied from 0.2 to 0.8. There were no nighttime observations in our study to compare with this result.

In retrospect, the P-values increase with increasing instability (and increasing terrain roughness). Table 11 quoted from DeMarrais summarizes the relationship of P-values to atmospheric stability.

V. SUMMARY

Correlation analysis of windspeed in the Redstone Arsenal, Alabama boundary-layer along with the variation of the exponent in the power-law wind profile for concurrent tower, LDV, and pibal data are presented for 36 cases between 13 January and 1 April 1986. Wind profiles were available up to 90m, 450m, and 915m for the tower, LDV, and pibal data, respectively. The linear correlations between the windspeed (scalar wind, zonal and meridional components) near the surface and windspeed at altitudes above were computed. The correlation between the scalar wind at 4m with the scalar wind at 90m is .84 for the tower data (using first available observation from each set), improving to .92 when the scalar wind at 19m is in correlation with the scalar wind at 90m. The correlations derived from the LDV data set also showed the correlations improving as the reference point is raised, but the correlations were lower and dispersed over a wider range.

The mean and standard deviation of the exponent (P) in the power-law wind profile equation was calculated for each observation height. The overall mean P-value for the pibal data was .16, in close agreement with a value of 1/7 often quoted in the literature. There were more interlevel differences in the P-value for both the tower and LDV data sets. The overall mean P-value for the tower and LDV data were .11 and .07, respectively.

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TABLE 1. Correlations of Wind at 4m With Winds Above for Pibal and Tower Data (r_s: Scalar Windspeed, r_z: Zonal Components, r_m: Meridional Components)

Height(m)	Pibal r_s	Pibal r_z	Pibal r_m	Tower r_s	Tower r_z	Tower r_m
34	.95	.97	.96	.88	.91	.86
61	.86	.94	.92	.88	.90	.85
90	.84	.91	.89	.86	.88	.83
153	.87	.93	.90			
240	.84	.88	.90			
336	.75	.80	.87			
450	.61	.76	.82			
480	.57	.73	.80			

TABLE 2(a). Correlations of Scalar Winds at 19 Meters with Winds Above for LDV and Tower Data

Case 1: All Available Observations (2-Minute Period for the Tower)

Case 2: First Observation Only (36 Observations Total)

Case 3: Approximate 2-Minute Average (36 Observations Total)

	1		2		3	
	LDV	TOWER	LDV	TOWER	LDV	TOWER
Height(m)						
34	.92	.95	.49	.95	.89	.99
61	.89	.93	.49	.94	.89	.99
90	.86	.91	.67	.92	.91	.97
153	.85		.53		.91	
240	.79		.39		.87	
336	.75		.53		.82	
450	.70		.30		.51	
480	.73		-.11		.59	

TABLE 2(a). Correlations of Scalar Winds at 19 Meters with Winds Above for LDV and Tower Data (Concluded)

Case 1: All Available Observations (2-Minute Period for the Tower)

Case 2: First Observation Only (36 Observations Total)

Case 3: Approximate 2-Minute Average (36 Observations Total)

	1		2		3	
	LDV	TOWER	LDV	TOWER	LDV	TOWER
Height(m)						
34	.92	.95	.49	.95	.89	.99
61	.89	.93	.49	.94	.89	.99
90	.86	.91	.67	.92	.91	.97
153	.85		.53		.91	
240	.79		.39		.87	
336	.75		.53		.82	
450	.70		.30		.51	
480	.73		-.11		.59	

TABLE 2(b). Correlations of Windspeed at 19m with Windspeeds Above Using the 1st, 2nd, 3rd, and 4th Wind Profiles Available From each LDV Data Set (Scalar Windspeed Only)

	r_s			
Height(m)	1	2	3	4
34	.49	.66	.85	.91
61	.49	.66	.85	.91
90	.67	.64	.88	.90
153	.53	.68	.91	.90
240	.39	.86	.85	.90
336	.53	.82	.83	.88
450	.30	.31	.57	-.04
480	-.11	.51	.65	.70

TABLE 2(c). Correlations of Windspeed at 19m With Windspeeds Above Using the 1st, 2nd, 3rd, and 4th Wind Profiles Available From Each Tower Data Set (Scalar Windspeed Only)

	r_s			
Height(m)	1	2	3	4
34m	.95	.94	.96	.96
61	.94	.93	.93	.93
90	.92	.92	.93	.94

TABLE 3. Correlations of Windspeeds at 4 Meters, 10 Meters, and 19 Meters With Winds Above for Tower Data (r_s: Scalar Windspeed, r_s: Zonal Components, r_m: Meridional Components)

Case 1: All Available Observations (2-Minute Period)

Case 2: First Observation Only (36 Observations Total)

1

Height(m)	4m			10m			19m		
	r_s	r_z	r_m						
10	.93	.93	.89	r_s	r_z	r_m			
19	.91	.92	.87	.98	.98	.98	r_s	r_z	r_m
34	.88	.91	.86	.94	.97	.96	.95	.98	.97
61	.88	.90	.85	.92	.95	.95	.93	.96	.95
90	.86	.88	.83	.90	.94	.93	.91	.95	.94

2

Height(m)	4m			10m			19m		
	r_s	r_z	r_m						
10	.90	.95	.97	r_s	r_z	r_m			
19	.89	.95	.96	.96	.99	.98	r_s	r_z	r_m
34	.86	.94	.94	.92	.97	.96	.95	.98	.96
61	.85	.93	.91	.89	.97	.93	.94	.97	.94
90	.84	.91	.91	.91	.95	.94	.92	.95	.95

TABLE 4. Correlation of 4 Meters Surface Pibal Winds With Tower Winds Above (r_s: Scalar Windspeed, r_z: Zonal Components, r_m: Meridional Components) - First Tower Observation

Height(m)	r_s	r_z	r_m
10	.76	.81	.86
19	.76	.79	.85
34	.78	.82	.90
61	.81	.83	.89
90	.83	.86	.89

TABLE 5. Correlations of 34m, 61m, and 90m Winds With Winds Above for Pibal Data (r_s: Scalar Windspeed, r_z: Zonal Components, r_m: Meridional Components)

34m

Height(m)	r_s	r_z	r_m
61m	.96	.98	.98
90	.94	.97	.97
153	.95	.96	.97
240	.89	.91	.93
336	.79	.85	.88

61m

Height(m)	r_s	r_z	r_m
90m	.99	.99	.99
153	.97	.98	.98
240	.88	.83	.92
336	.75	.87	.85

90m

Height(m)	r_s	r_z	r_m
153m	.97	.98	.99
240	.88	.93	.91
336	.75	.87	.85

TABLE 6. Correlations of 34m and 61m Winds With Winds Above for Tower Data (r_s: Scalar Windspeed, r_z: Zonal Components, r_m: Meridional Components)

	34m				61m		
Height(m)	r_s	r_z	r_m	Height(m)	r_s	r_z	r_m
61m	.99	.99	.93	90m	.98	.99	.93
90	.96	.98	.98				

TABLE 7. Correlations of 34m, 61m, and 90m Tower Winds With Pibal Winds Above (r_s: Scalar Windspeed, r_z: Zonal Components, r_m: Meridional Components)

34m

Height(m)	r_s	r_z	r_m
61m	.79	.91	.80
90	.79	.91	.79
153	.82	.90	.77
240	.80	.84	.76
336	.73	.74	.72

61m

Height(m)	r_s	r_z	r_m
90m	.80	.93	.86
153	.83	.92	.88
240	.81	.87	.87
336	.74	.79	.85

90m

Height(m)	r_s	r_z	r_m
153m	.83	.89	.77
240	.84	.84	.77
336	.78	.78	.73

TABLE 8. Correlations of 34, 61, and 90m Winds With Winds Above for LDV Data (r_s: Scalar Windspeed, r_s: Zonal Components, r_m: Meridional Components)

34m

Height(m)	r_s	r_z	r_m
61m	.91	.88	.82
90	.94	.90	.79
153	.86	.92	.82
240	.78	.88	.80
336	.77	.85	.69

61m

Height(m)	r_s	r_z	r_m
90m	.84	.88	.84
153	.96	.93	.88
240	.88	.87	.85
336	.81	.86	.74

90m

Height(m)	r_s	r_z	r_m
153	.91	.95	.82
240	.85	.89	.85
336	.82	.87	.75

TABLE 9(a). Mean and Standard Deviation of the Exponent (P) in the Power-Law Wind Profile Derived from the Anemometer (Tower) Data. (The Reference Point is 4 Meters)

Height (Meters)	Mean	Population Standard Deviation
10m	.173	.149
19	.111	.117
34	.113	.117
61	.060	.075
90	.080	.079

TABLE 9(b). Mean and Standard Deviation of the Exponent (P) in the Power-Law Wind Profile Derived from the Pibal Data. (The Reference Point is 4 Meters)

Height(Feet)	Mean	Population Standard Deviation
100	.093	.085
200	.129	.122
300	.164	.124
400	.157	.117
500	.153	.108
600	.159	.104
700	.167	.088
800	.169	.095
900	.173	.103
1000	.171	.094
1100	.178	.097
1200	.175	.093
1300	.169	.088
1400	.164	.099
1500	.149	.105
2000	.164	.115
2500	.166	.121
3000	.172	.108

TABLE 10. Mean and Standard Deviation of the Exponent in the Power-Law Wind Profile (P) Derived from the LDV Data (The Reference Point is 19 Meters)

Height(Meters)	Mean	Population Standard Deviation
34m	.069	.386
61	.055	.132
90	.092	.154
153	.074	.084
240	.067	.080
336	.081	.087
450	.024	.219
480	.079	.174

TABLE 11. Values of P Determined at Various Locations (From DeMarrais, 1959)

a. Values of P According to Four Temperature Lapse-Rate Conditions

b. Values of P According to Day and Night

(a)

Site	Super-adiabatic	Neutral	Stable	Inversion	Height Range	Terrain	Notes
Quickborn, Germany	0.25	0.27	-	0.61	10-70m	Meadows	Tower observations
Tallmadge, Ohio	0.16	0.20	0.25	0.36	11-49m	Flat Field	Tower observations
Hanford, Washington	0.09	0.12	0.14	0.25	15-122m	Mountainous	Tower observations
Cardington, England	0.15	0.17	0.27	0.32-0.77	8-120m	Grass Field	Tower observations
Harwell, England	0.09	0.08	0.18	-	9-27m	Airfield	Tower observations
Idaho Falls, Idaho	0.15	0.18	0.22	-	9-61m	Desert	Tower observations
Brookhaven	0.19	0.29	0.35	0-46-0.59	11-124m	Forest	Tower observations

(b)

Site	Day	Night	Observed	Height Range	Terrain	Notes
Nauen, Germany	0.06	0.31	Winter	32-123m	Flat meadow	Tower observations
Nauen, Germany	0.11	0.60	Summer	32-123m	Flat meadow	Tower observations
Harwell, England	0.14	-	-	61-152m	Constr. site	Captive balloon
Sale, Australia	0.14	0.21	Fall	12-153m	Grazing land	Tower observations
Leafield, England	0.20	0.30	Winter	13-95m	Grass field	Tower observations
Leafield, England	0.16	0.36	Summer	13-95m	Grass field	Tower observations
Oak Ridge, Tenn.	0.24	0.71	All year	53-160m	Mountainous	Pibal observations

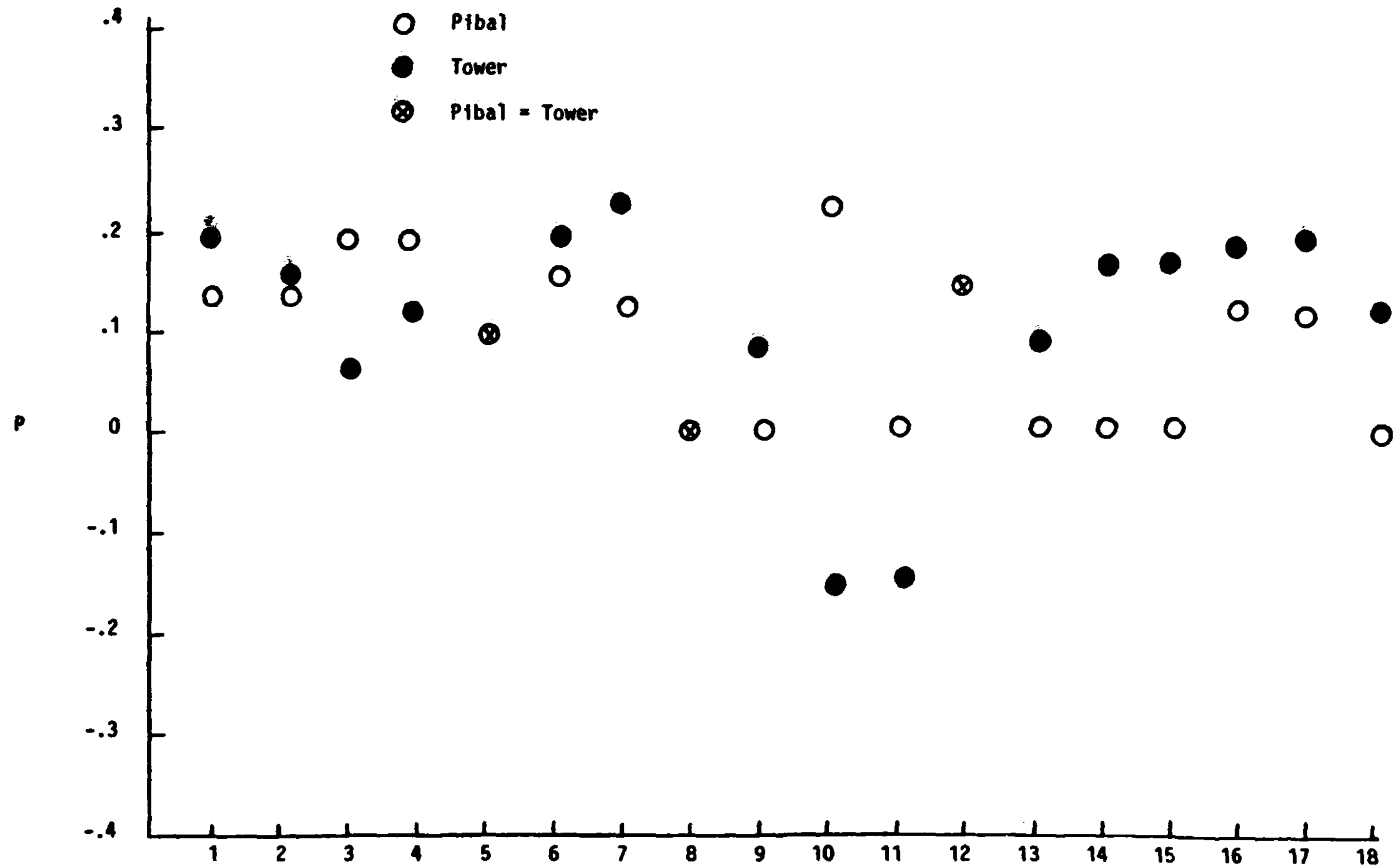

Figure 1.a. The exponent P in Equation (1) from the pibal and tower data at 34 m (observations 1-18).

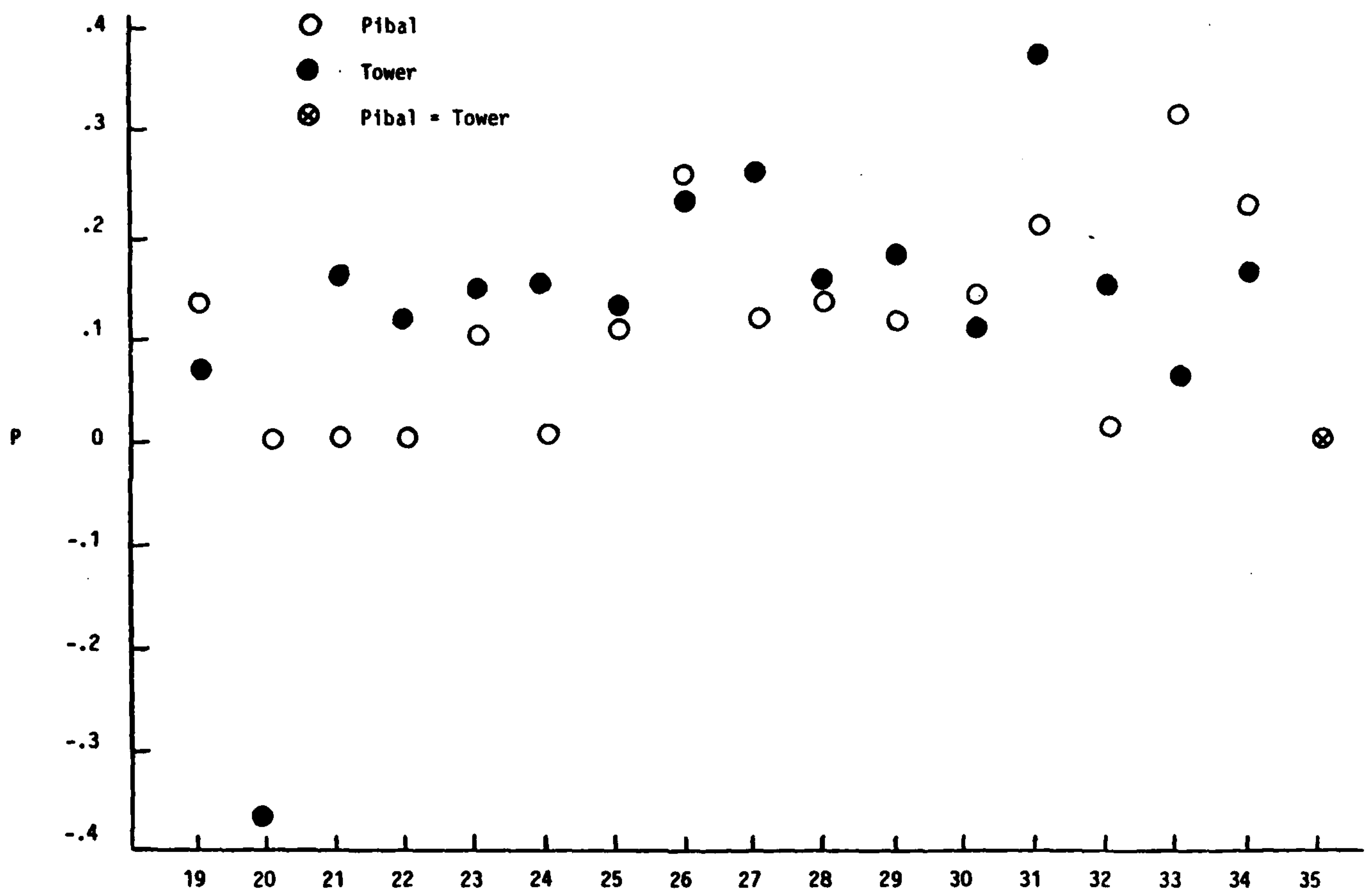

Figure 1.b. The exponent P in Equation (1) from the pibal and tower data at 34 m (observations 19-35).

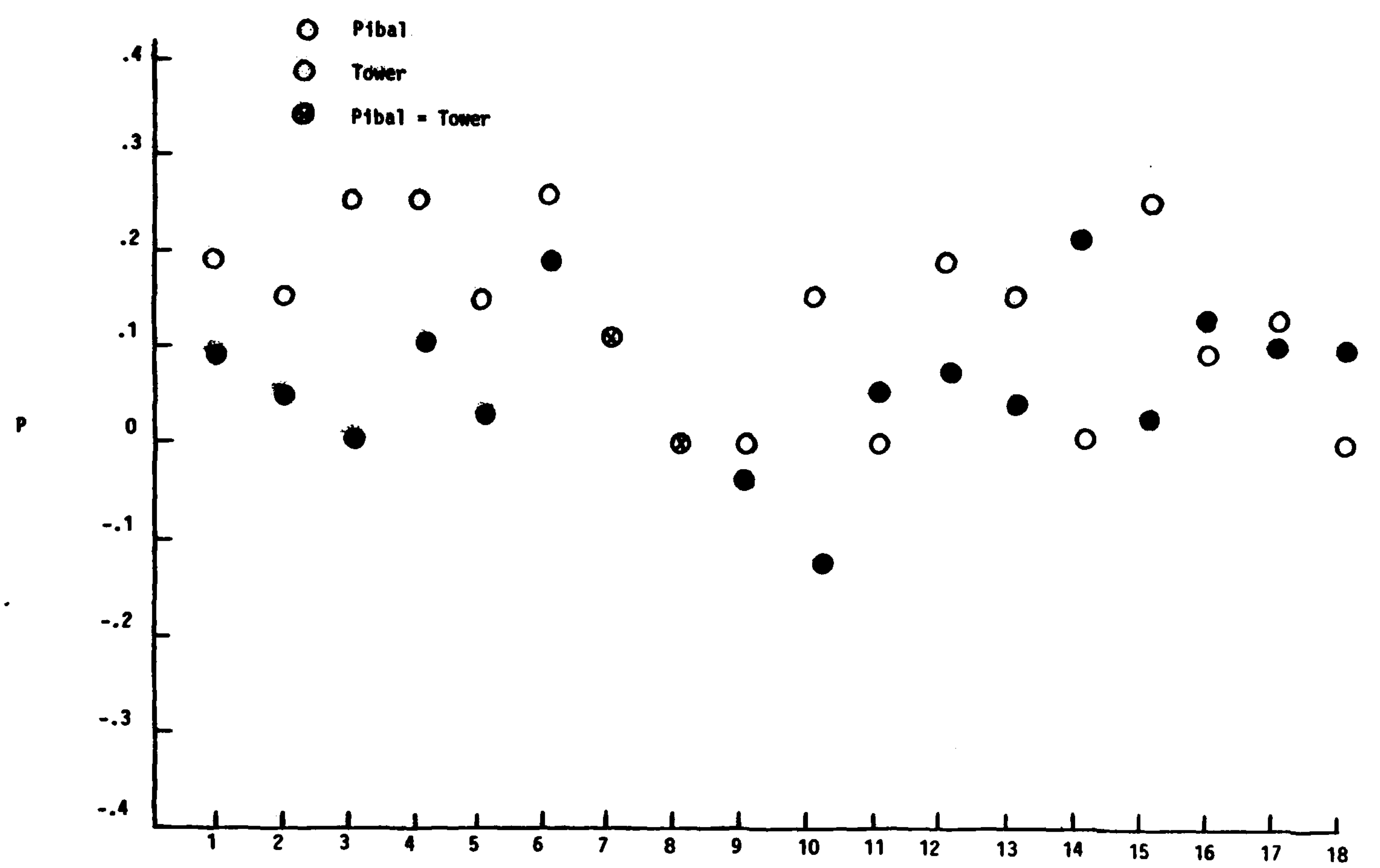

Figure 2.a. The exponent P in Equation (1) from the pibal and tower data at 61 m (observations 1-18).

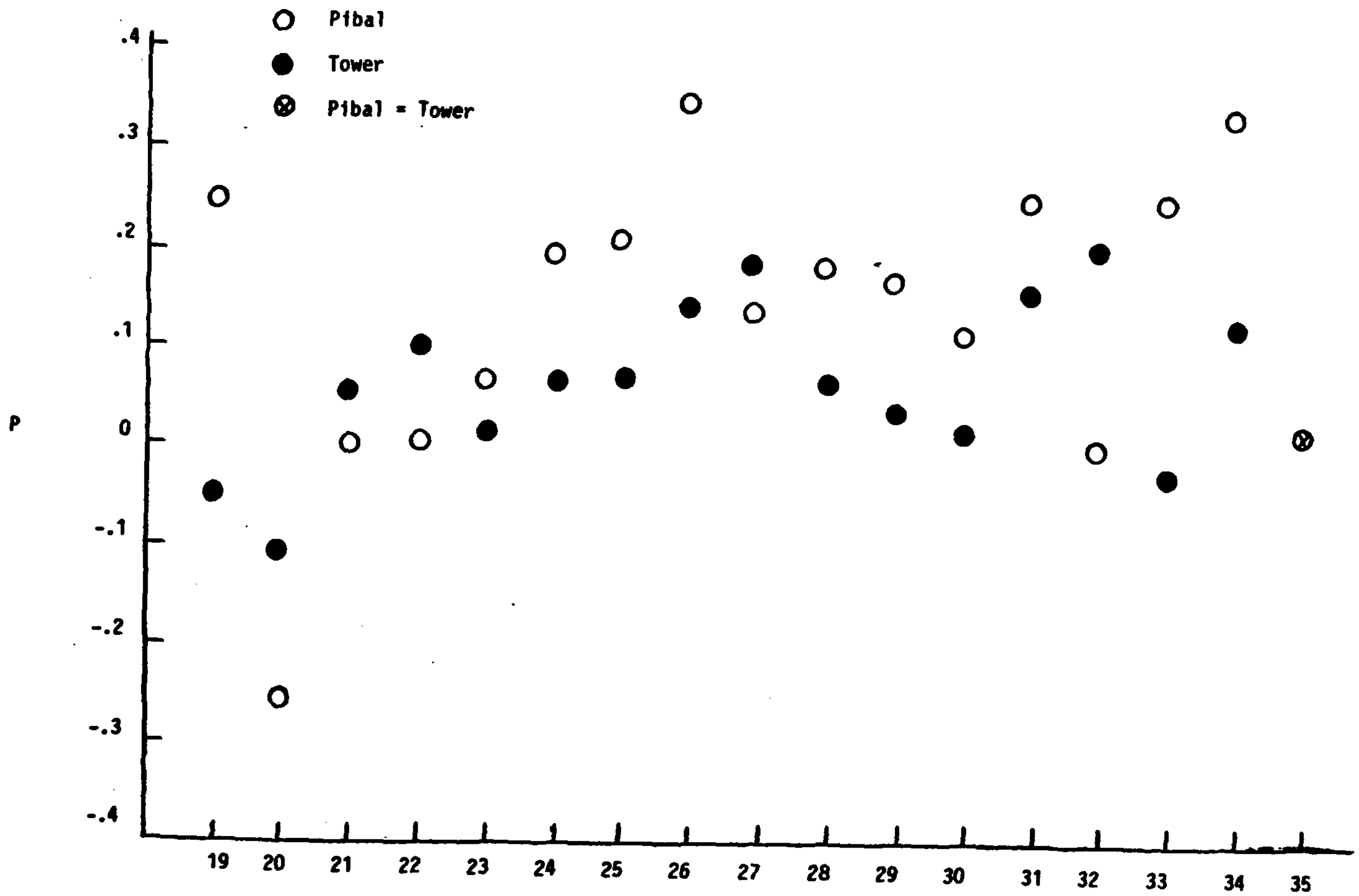

Figure 2.b. The exponent P in Equation (1) from the pibal and tower data at 61 m observations 19-35).

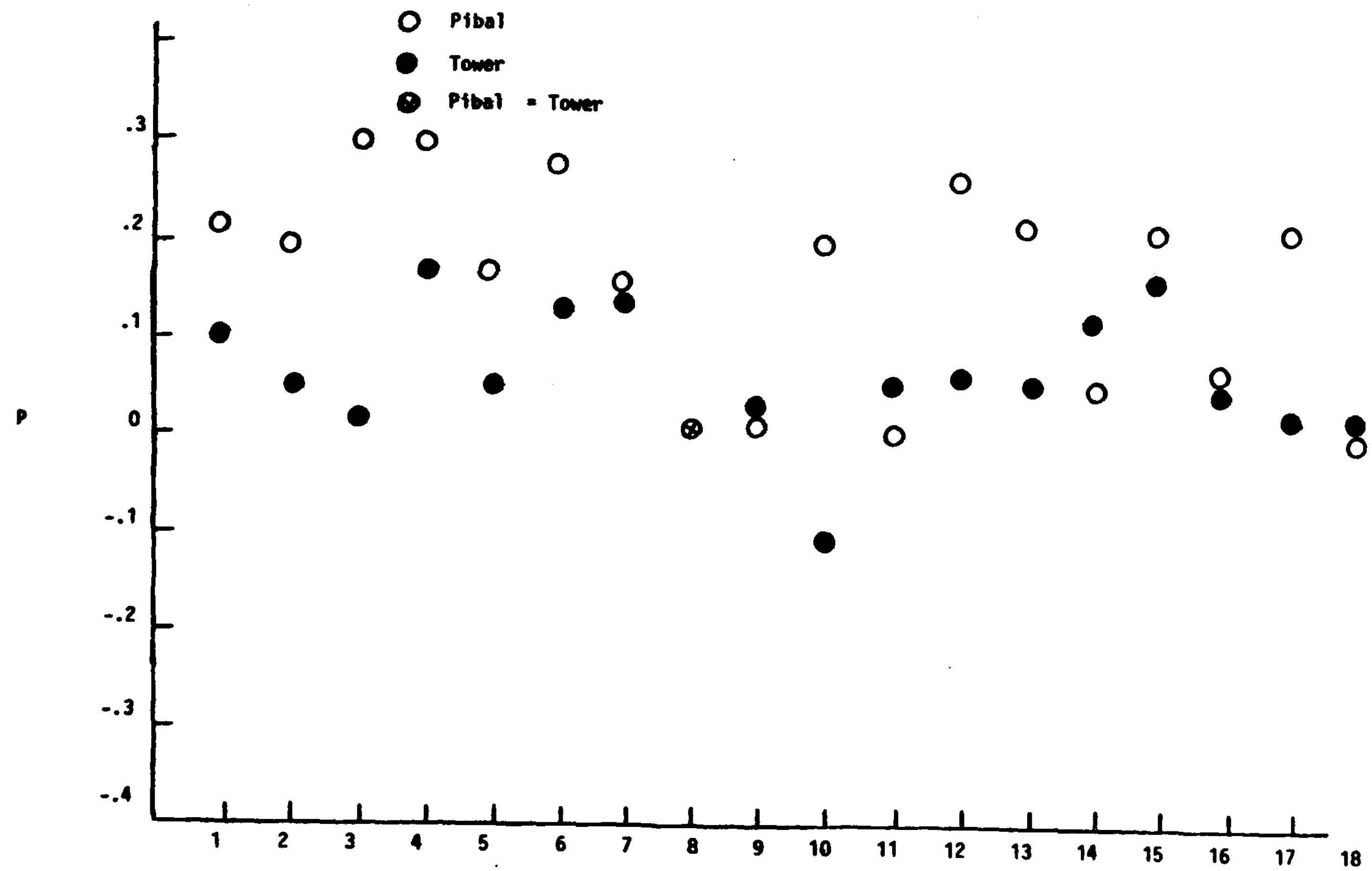

Figure 3.a. <u>The exponent P in Equation (1) from the pibal and tower data at 90 m (Observations 1-18).</u>

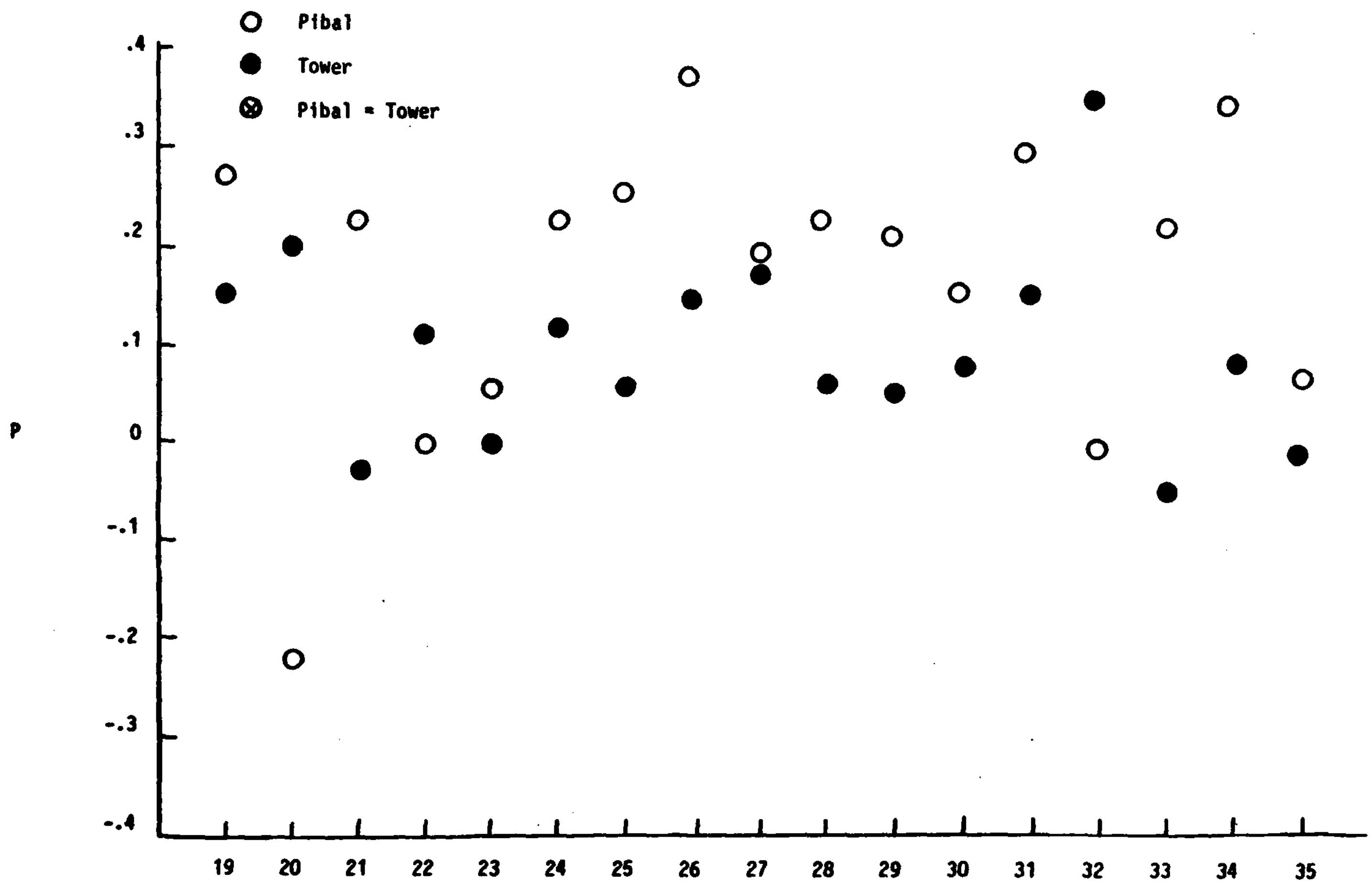

Figure 3.b. The exponent P in Equation (1) from the pibal and tower data at 90 m (observations 19-35).

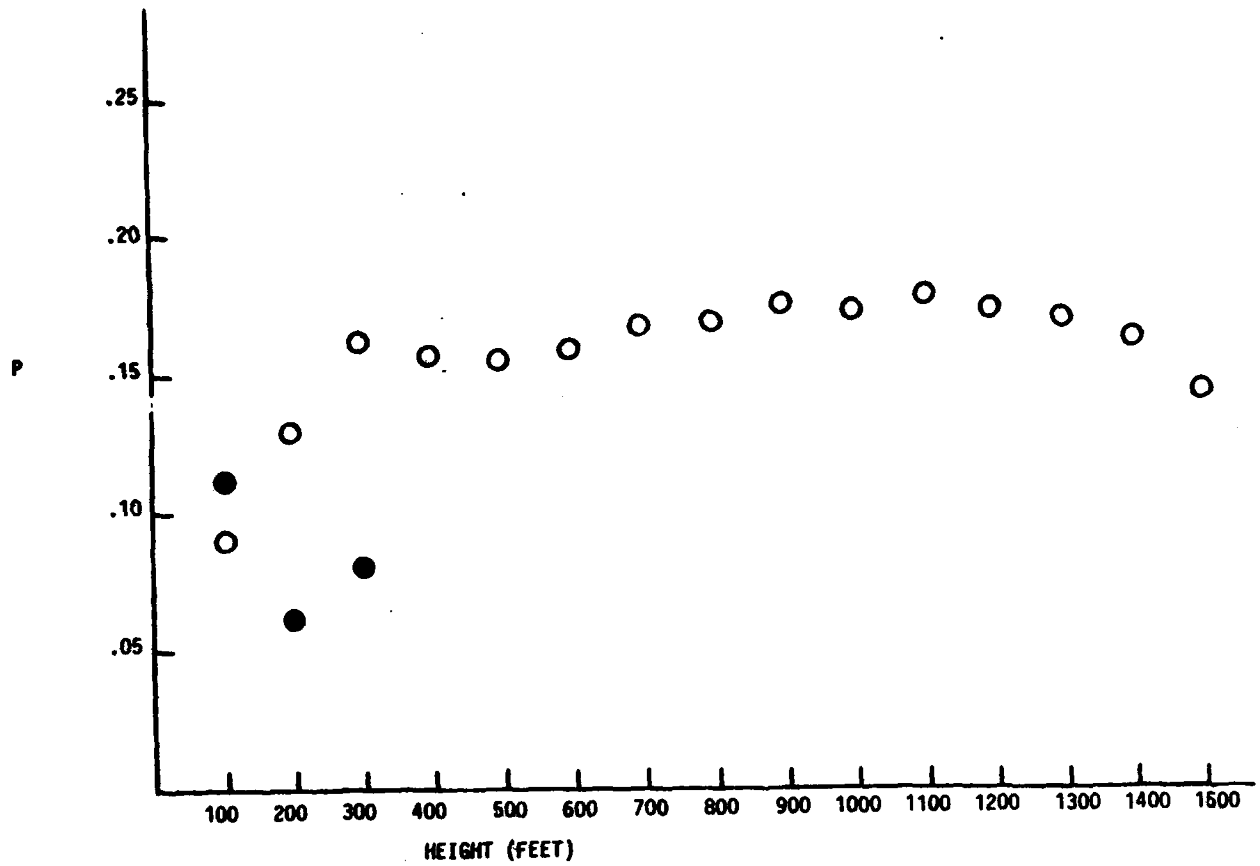

Figure 4. Mean value of the exponent P in Equation (1) for the 35 simultaneous pibal and tower windspeed observations at the indicated altitudes (feet).

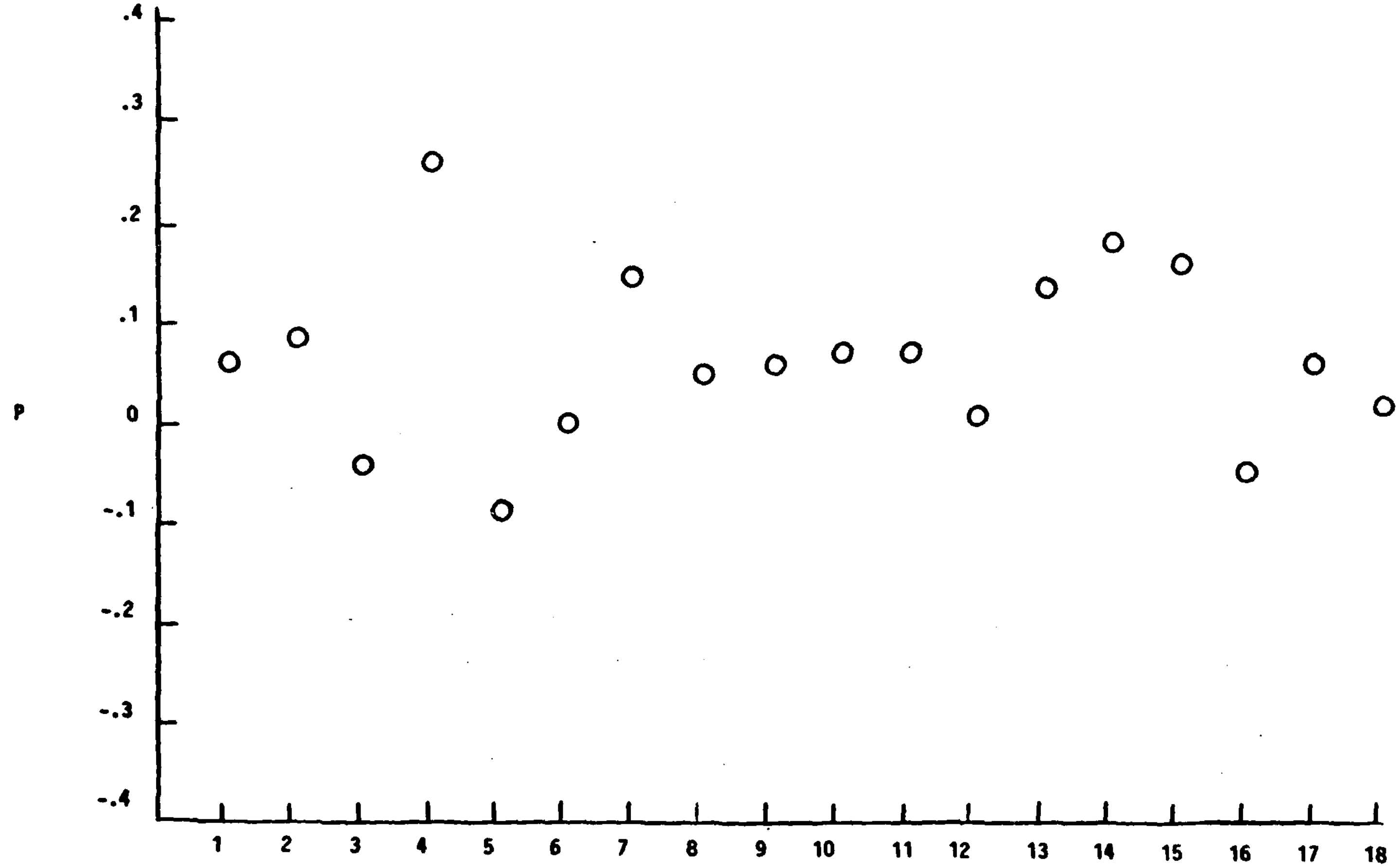

Figure 5.a. The exponent P in Equation (1) from the LDV data at 153 m (observations 1-18).

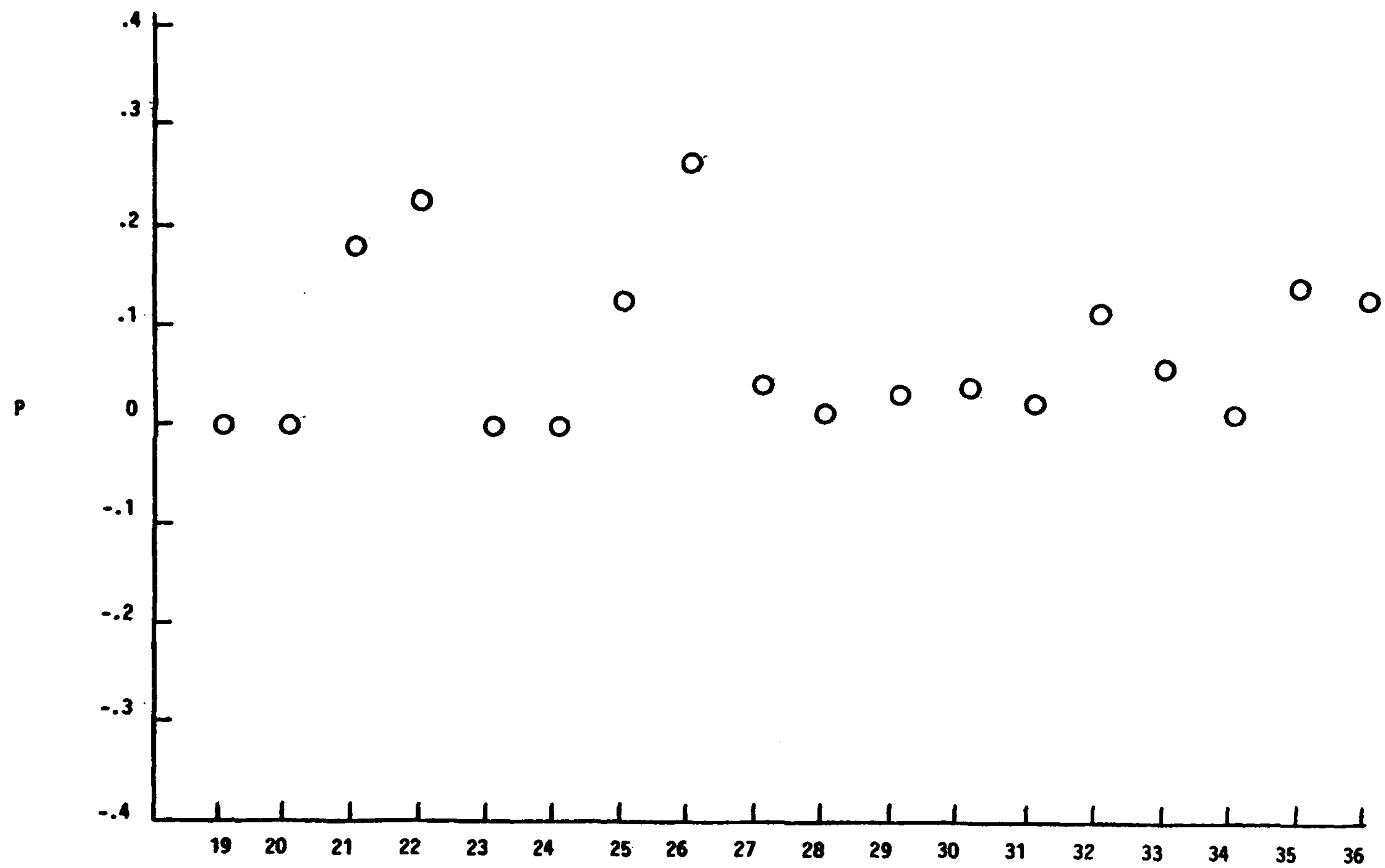

Figure 5.b. The exponent P in Equation (1) from the LDV data at 153 m (observations 19-36).

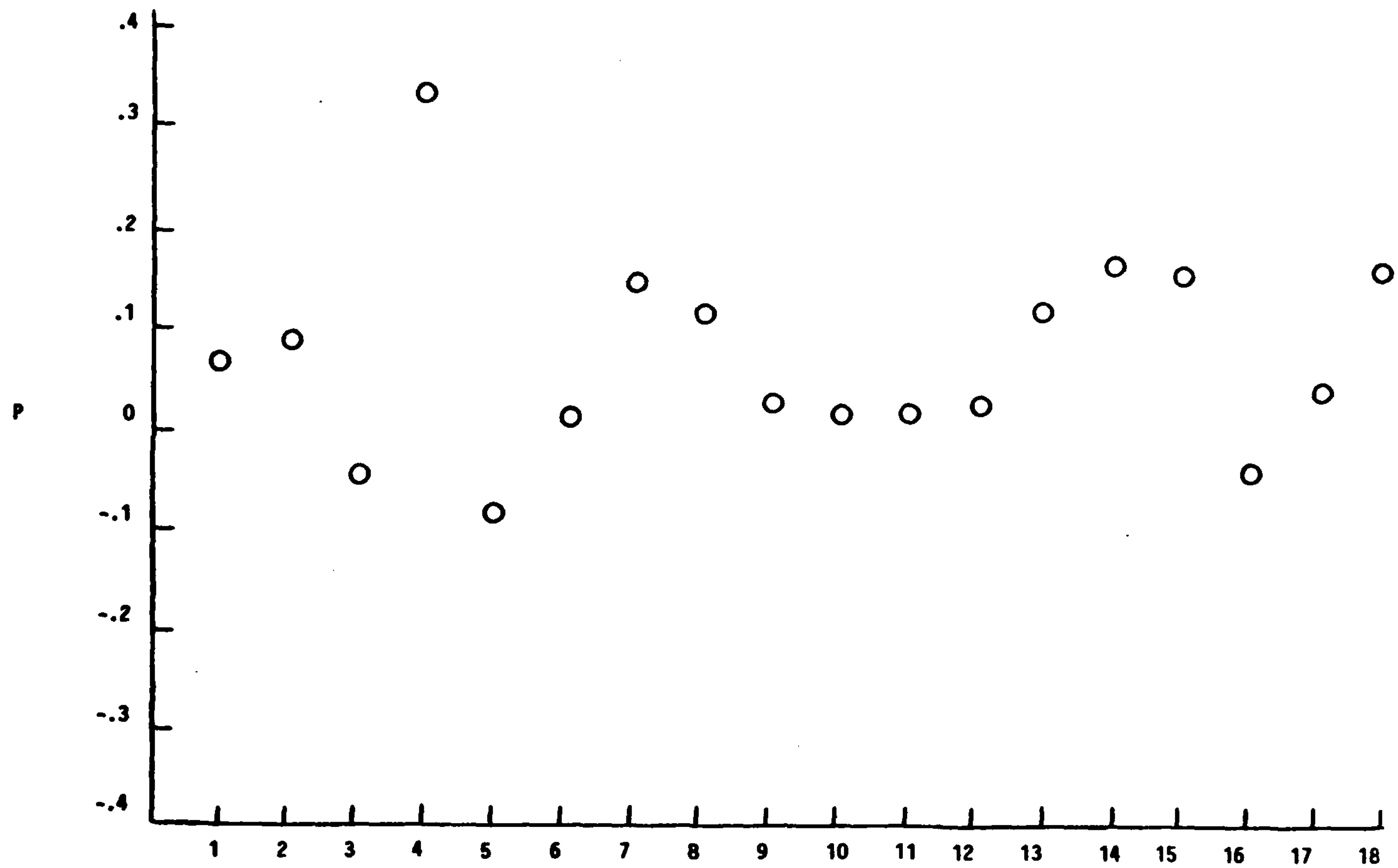

Figure 6.a. The exponent P in Equation (1) from the LDV data at 240 m (observations 1-18).

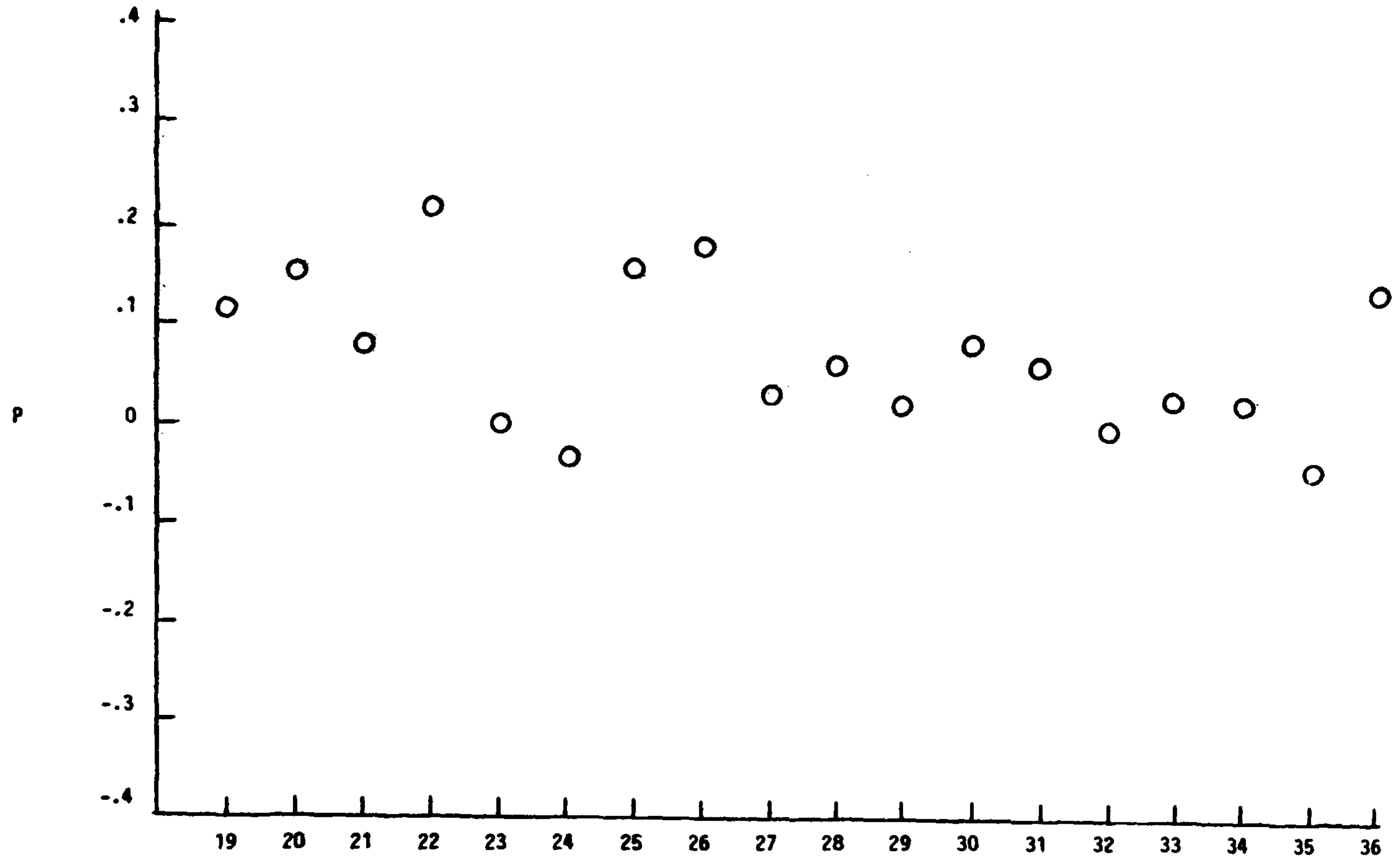

Figure 6.b. The exponent P in Equation (1) from the LDV data at 240 m (observations 19-36).

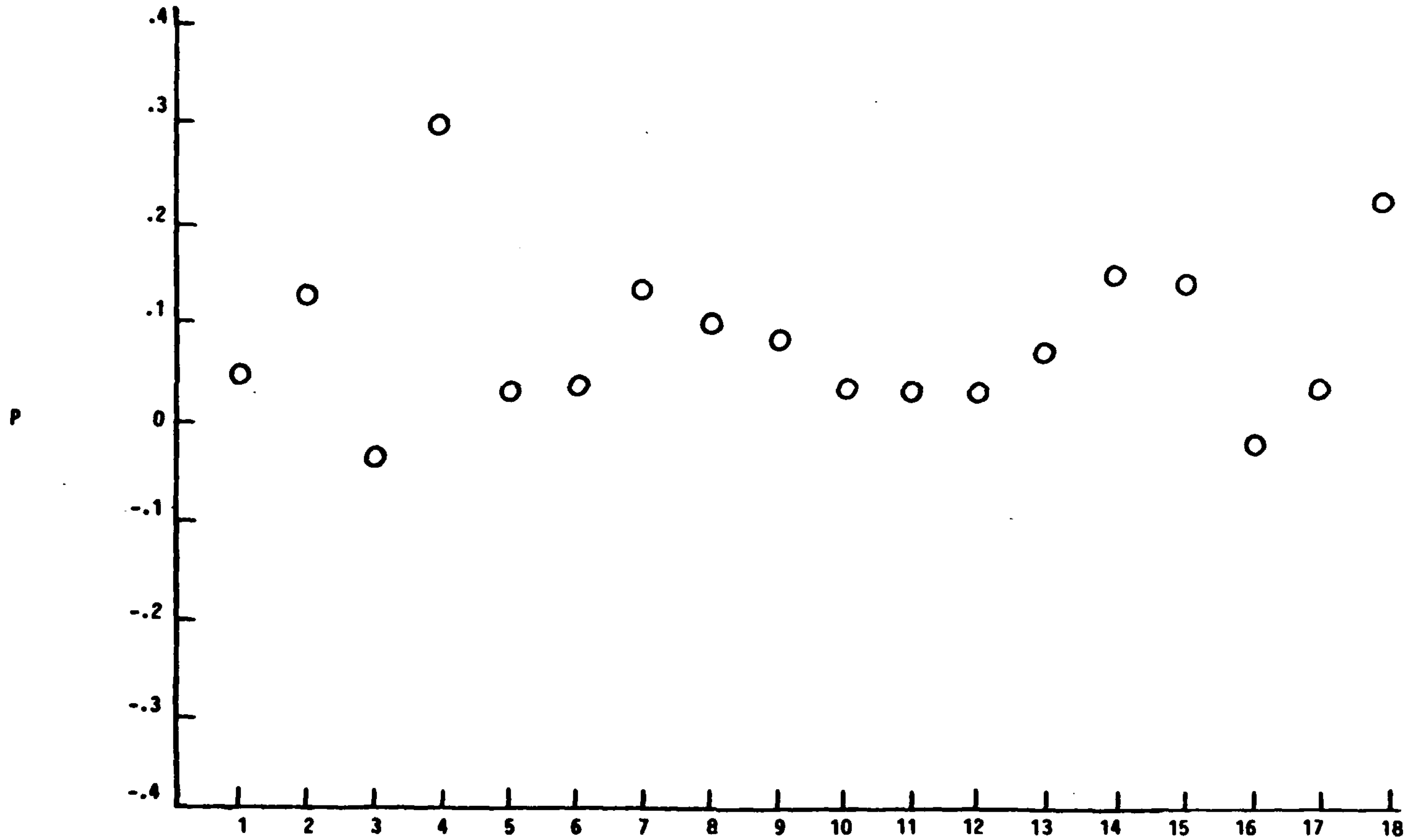

Figure 7.a. The exponent P in Equation (1) from the LDV data at 336 m (observations 1-18).

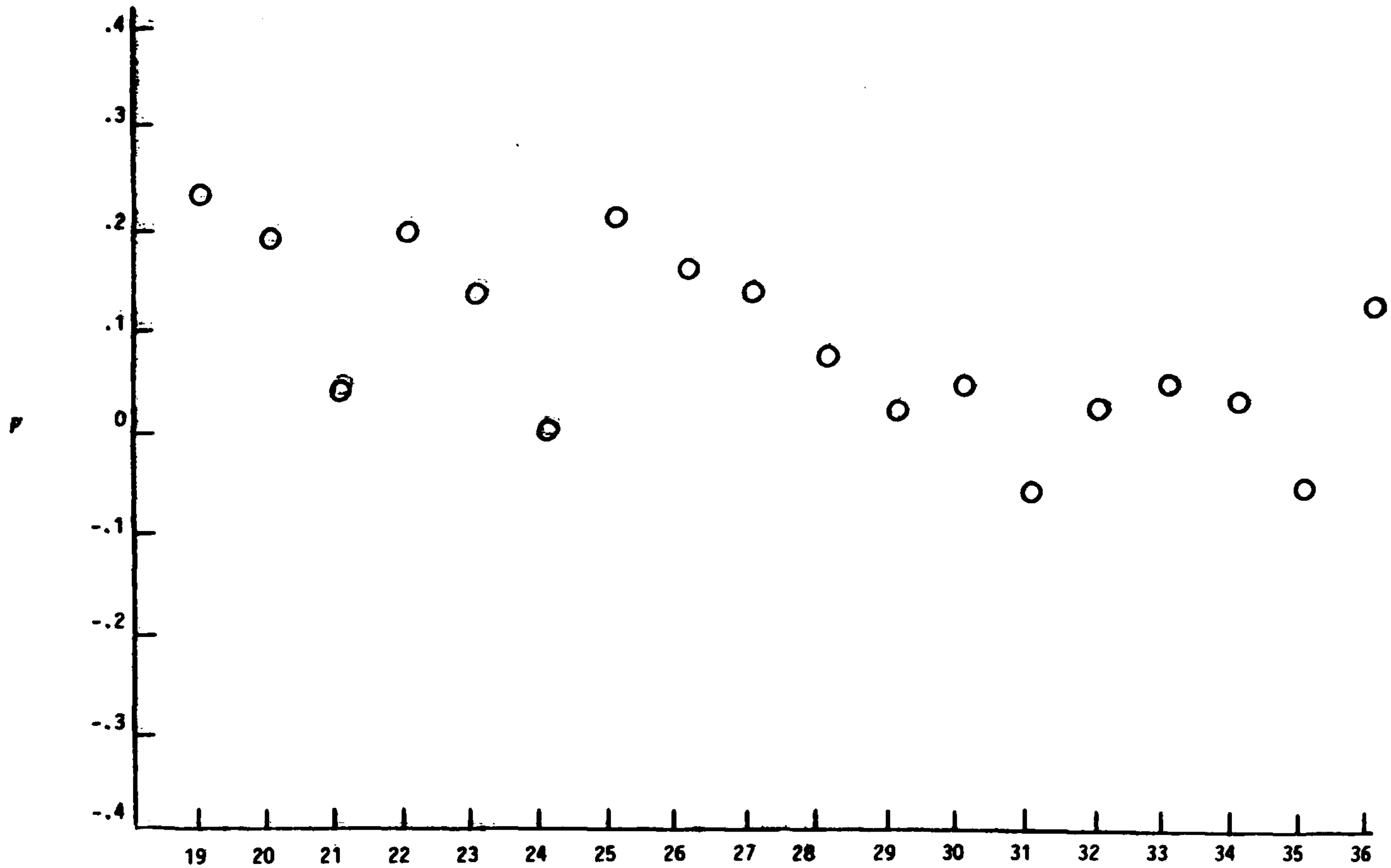

Figure 7.b. The exponent P in Equation (1) from the LDV data at 336 m (observations 19-36).

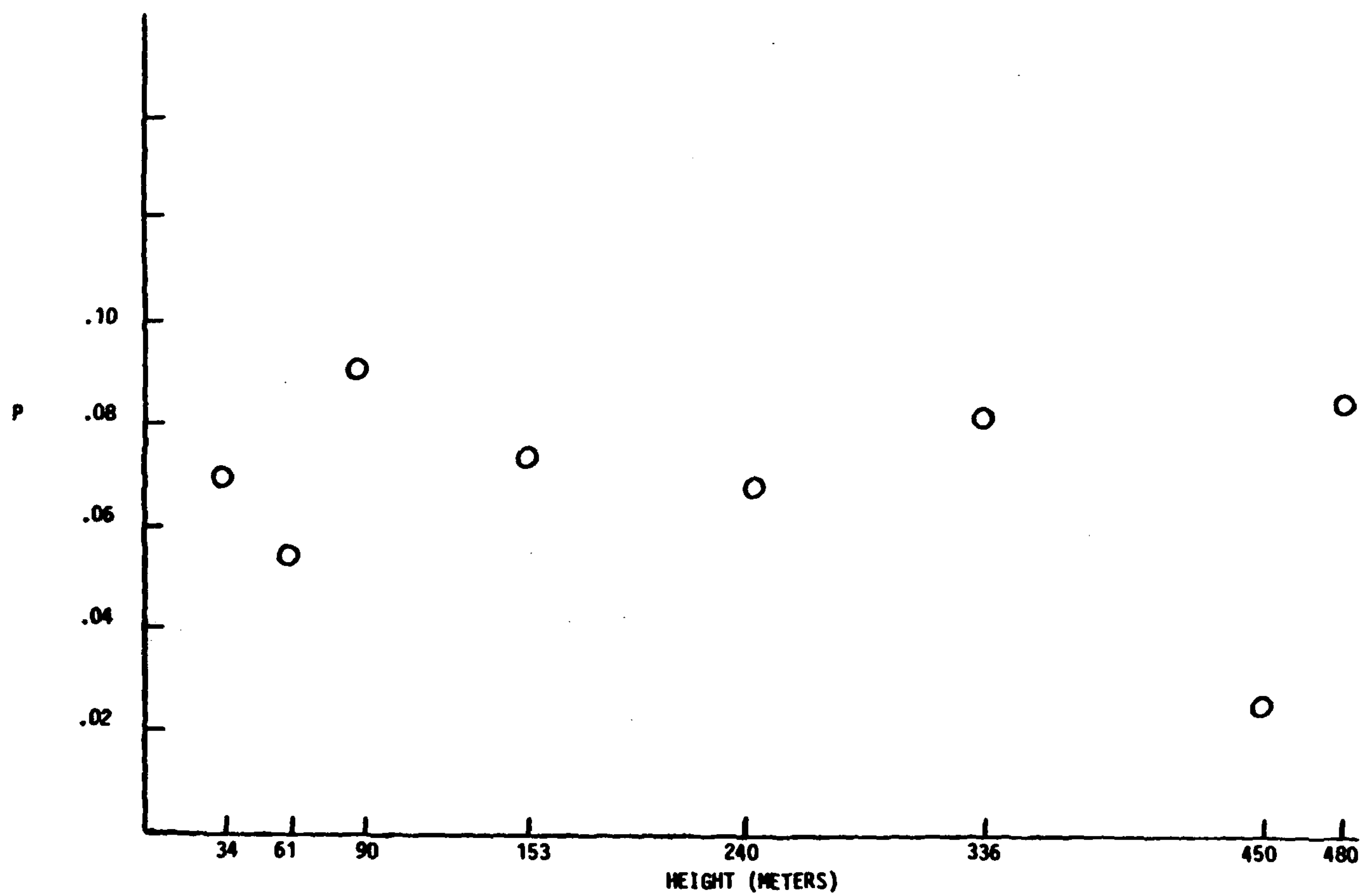

Figure 8. Mean value of the exponent P in Equation (1) for the LDV windspeed observations at the indicated altitudes (meters).

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